

STRUCTURAL PERFORMANCE AND DESIGN OF HYBRID STAINLESS STEEL GIRDERS UNDER LOCALISED FORCES

Xiao-Wen Xu ¹, Xiao-Yong Sun ¹, Jian-Hang Fu ^{1,*}, You-Tian Wang ², Zhao-Yang Xi ³,
Zhi-Ping Fu ³, Song-Yang Bi ³ and Bo-Shan Chen ³

¹ Department of Civil Engineering, Hebei University of Water Resources and Electric Engineering, P.R. China

² Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region of China, P.R. China

³ School of Civil Engineering and Architecture, Hainan University, P.R. China

* (Corresponding author: E-mail: tmx1401@163.com)

ABSTRACT

A novel generation of hybrid stainless steel girders, featuring high-strength stainless steel flanges and conventional stainless steel webs, has been developed and is increasingly used in marine structures. This hybrid configuration provides enhanced flexural capacity while simultaneously reducing material consumption and structural weight compared with conventional homogeneous girders. However, no established design rules currently exist for such hybrid steel girders. As a result, the resistance and design of such hybrid stainless steel girders under localised forces should be carefully evaluated. This study aims to fill the gap by expanding on previous experimental work and proposing simplified design methods for predicting the resistance of hybrid stainless steel girders under localised forces using numerical methods. A robust finite element (FE) model, previously developed and validated by the authors, was utilized to conduct an extensive parametric study, generating a total of 1248 FE results. This study focused on key parameters, including the bearing width ratio, web aspect ratio, web slenderness, and local geometric imperfection. The numerical results were analysed to assess the reliability of existing design guidelines, namely GB 50017-2017, EN 1993-1-5, and ANSI/AISC 360-22. The analysis revealed that the predicted values from GB 50017-2017 were unconservative, with an average deviation of 16.4%. In contrast, EN 1993-1-5 (2006) and ANSI/AISC 360-22 (2022) provided conservative estimates, with average deviations of 44.7% and 19.8%, respectively. To address this issue, new design proposals were formulated, incorporating a modified coefficient within the framework of existing design rules.

Copyright © 2026 by The Hong Kong Institute of Steel Construction. All rights reserved.

ARTICLE HISTORY

Received: 24 May 2025
Revised: 3 January 2026
Accepted: 4 January 2026

KEYWORDS

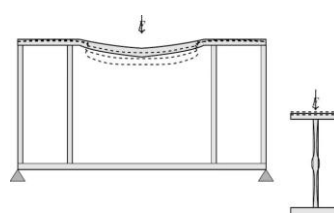
Hybrid stainless steel girders;
Localised force, numerical method;
New design proposals;
Parametric study

1. Introduction

A novel generation of hybrid stainless steel girders, featuring high-strength stainless steel flanges and conventional stainless steel webs, has been developed and is increasingly used in marine structures. Stainless steel is attractive for structural applications in aggressive marine environments [1]. This hybrid configuration offers clear structural advantages by providing enhanced flexural capacity while simultaneously reducing material consumption and structural weight compared with fully homogeneous girders [2]. However, hybrid-configured girders may experience buckling failure due to patch loading when exposed to moving loads, in which a concentrated force applied perpendicular to the flange leads to localized web failure [3-8], as illustrated in Fig. 1. The issue is especially common with crane girders and beam-column couplings. Therefore, a comprehensive assessment of the buckling behavior of hybrid stainless steel girders under localized bearing force is required.



(a) Steel girders used in marine structures



(b) Schematic diagram

Fig. 1 The practical application and loading cases of steel girders

The structural behavior of hybrid carbon steel members has been the subject of numerous investigations in the literature [9–13], revealing notable performance distinctions compared to their homogeneous counterparts. Nevertheless, studies on hybrid steel members incorporating conventional stainless steel remain relatively scarce. Lalthazuala and Singh [14–16] performed a series of numerical investigations to evaluate the structural performance and design behavior of hybrid-configured girders, with particular emphasis on bending, axial compression, and shear capacity. Based on their numerical results, refined design formulations tailored to hybrid members were proposed. In parallel, Bock et al. [17] carried out numerical analyses on hybrid stainless steel girders subjected to compression and bending. However, the validation of their numerical models was based exclusively on experimental results from homogeneous welded I-sections, rather than on specimens with hybrid material configurations. The lack of direct experimental evidence for

hybrid-configured girders therefore limits the reliability and general applicability.

To date, no studies have addressed the resistance of hybrid stainless steel girders under localized forces. While the authors' prior research [18-22] examined the structural behavior and design of homogeneous stainless steel girders, these investigations focused exclusively on patch loading and shear resistance in homogeneous members, which exhibit distinct characteristics compared to hybrid configurations. The variations in material composition, bonding mechanisms, and load distribution between hybrid and homogeneous girders highlight the need for a more comprehensive analysis of their performance under concentrated loads.

Furthermore, homogeneous girders are the main focus of the current design requirements for predicting girder resistance under localized loads [23-25]. Existing design standards, such as GB 50017 [26], EN 1993-1-5 [27], and ANSI/AISC 360-22 [28], are fundamentally developed based on the assumption of material homogeneity, which may not be fully applicable to hybrid stainless steel members. They do not consider the unique characteristics and performance variations inherent in hybrid-configured girders, which combine different material grades in their construction. Consequently, their applicability to hybrid-configured girders requires thorough evaluation in this study.

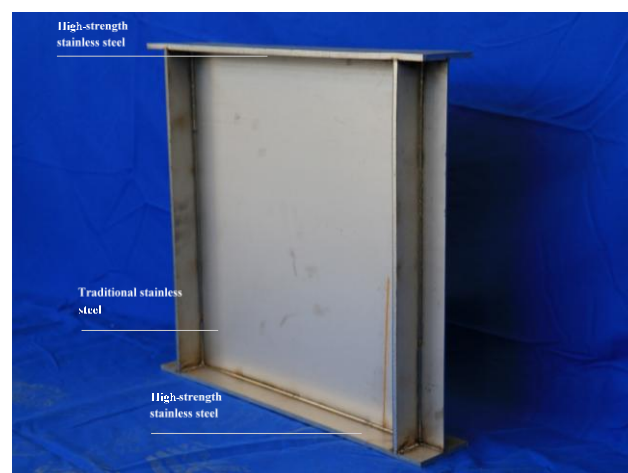


Fig. 2 Photograph of test specimens investigated in this study [29]

To address the aforementioned research gap, the present study builds upon

the authors' previous experimental investigations [29] and proposes simplified design approaches for evaluating the structural performance of hybrid stainless steel girders subjected to concentrated loading. The experimental specimens consist of high-strength stainless steel flanges combined with conventional stainless steel webs, as illustrated in Fig. 2. A previously developed and experimentally validated finite element (FE) model was subsequently employed to conduct an extensive parametric study, comprising a total of 1,248 numerical simulations. Through this comprehensive analysis, the influences of key parameters, including the bearing width ratio, web aspect ratio, web slenderness, and local geometric imperfections, were systematically investigated. Subsequently, the numerical predictions were systematically assessed to examine the suitability and predictive accuracy of the existing design provisions prescribed in GB 50017 [26], EN 1993-1-5 [27], and ANSI/AISC 360-22 [28]. Based on the observed discrepancies, calibration factors were introduced into the existing design formulations, and alternative design approaches were further proposed.

2. Numerical modelling

2.1. General

Numerical simulations using the ABAQUS program were performed to examine the structural response of hybrid-configured girders under localized bearing force [30]. The computational models underwent thorough validation through comparison with experimental data from the authors' prior studies [29],

incorporating considerations of material nonlinear behavior and initial geometric deviations. A detailed comparison of numerical predictions with experimental findings confirmed the accuracy of models in predicting the strength of such hybrid-configured girders. Further numerical modelling approaches can be found in the authors' recent studies [18,19].

2.2. Summary of test data for validation purposes

The authors' prior experimental program [29] involved testing 10 hybrid-configured girders under localized forces, as summarized in Table 1, with the data serving as a basis for subsequent validation. The flanges were fabricated from either QN1803 or S32001 high-strength stainless steel, while the webs were constructed using EN 1.4301 (S30408) or EN 1.4462 (S2205) conventional stainless steel.

A total of 22 tensile test specimens were extracted from specified locations on both the web and flange components, with testing procedures conducted in accordance with the British Standard for metallic material testing (ISO 6892-1) [31]. The corresponding tensile properties are summarized in Table 2. For the concentrated load testing, a 2000 kN MTS hydraulic press was utilized, as illustrated in Figs. 3 and 4. The investigation primarily examined failure behavior under an internal one-flange (IOF) loading condition applied at the beam's midspan. The girders were simply supported at both ends, with the concentrated force transmitted through a bearing plate. Displacement measurements were recorded using three LVDTs positioned at both ends and midpoint, as illustrated in Fig. 3.

Table 1
Summary of patch-loading test results reported by previous study [29]

Specimen ID	Flange material	Web material	L/mm	h_w/mm	a/mm	tw/mm	tf/mm	S_s/mm	w_0/mm	S_s/h_w	a/h_w	$P_{u,\text{Test}}/\text{kN}$
F1803W304-T3.0-ad1.0-S50-1	QN1803	EN 1.4301	600	500	500	2.95	7.77	50	0.5	0.10	1.0	99.7
F1803W304-T3.0-ad1.0-S50-2	QN1803	EN 1.4301	600	500	500	2.95	7.77	50	0.5	0.10	1.0	94.8
F1803W304-T3.0-ad1.0-S100-1	QN1803	EN 1.4301	600	500	500	2.94	7.75	100	0.3	0.20	1.0	108.6
F1803W304-T3.0-ad1.0-S100-2	QN1803	EN 1.4301	600	500	500	2.94	7.75	100	0.3	0.20	1.0	110.4
F32001W2205-T3.0-ad1.0-S50-1	S32001	EN 1.4462	600	500	500	3.00	7.78	50	1.0	0.10	1.0	164.2
F32001W2205-T3.0-ad1.0-S50-2	S32001	EN 1.4462	600	500	500	3.00	7.78	50	1.0	0.10	1.0	163.6
F32001W2205-T3.0-ad1.0-S100-1	S32001	EN 1.4462	600	500	500	3.00	7.75	100	0.6	0.20	1.0	173.9
F32001W2205-T3.0-ad1.0-S100-2	S32001	EN 1.4462	600	500	500	3.00	7.75	100	0.6	0.20	1.0	173.1
F32001W2205-T3.0-ad1.5-S100-1	S32001	EN 1.4462	850	500	750	2.98	7.76	100	1.2	0.20	1.5	167.9
F32001W2205-T3.0-ad1.5-S100-2	S32001	EN 1.4462	850	500	750	2.98	7.76	100	1.2	0.20	1.5	164.5

Table 2
Summary of material properties of hybrid stainless steel girders [20,24,37]

Grades	Coupon ID	E_0/GPa	$\sigma_{0.2}/\text{MPa}$	σ_u/MPa
QN1803	1803-T3-1	193.4	445.1	763.6
	1803-T3-2	191.3	437.5	749.1
	1803-T3-3	193.7	423.6	752.6
	1803-T8-1	187.1	415.6	703.5
	1803-T8-2	185.7	413.3	714.7
	1803-T8-3	182.4	406.9	708.8
S32001	32001-T3-1	187.9	475.1	674.6
	32001-T3-2	187.5	479.7	654.9
	32001-T3-3	180.8	476.9	666.8
	32001-T8-1	200.7	478.1	673.9
	32001-T8-2	191.1	481.5	680.8
	32001-T8-3	198.9	464.3	677.1
S30408	S30408-T3-1	187.5	306.7	716.5
	S30408-T3-2	180.2	300.7	714.3

EN 1.4301	S30408-T8-1	180.8	332.5	715.4
	S30408-T8-2	182.8	321.8	689.5
	S30408-T8-3	184.7	324.2	727.1
EN 1.4462	2205-T3-1	198.6	593.1	788.0
	2205-T3-2	202.2	598.5	795.4
	2205-T3-3	200.1	619.7	789.7
	2205-T8-1	202.7	559.1	776.7
	2205-T8-2	200.8	552.9	753.6

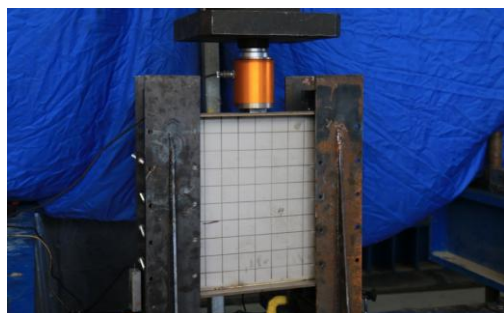


Fig. 3 Experimental setup from the authors [29]

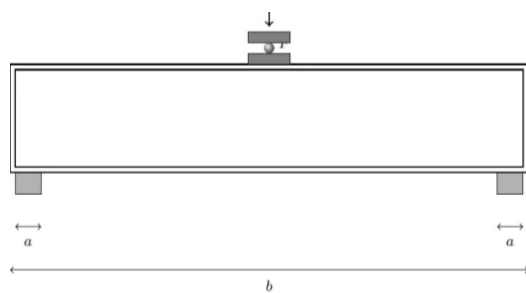


Fig. 4 Schematic diagram of the testing setup

Each girder specimen was tested following a two-stage loading protocol to fully exploit its structural capacity. In the first stage, the specimen was loaded in its as-fabricated orientation without any prior damage. Taking specimen F1803W304-T3.0-ad1.0-S50-1 as a representative example, the initial test was conducted until the peak load was attained. After completion of the first loading stage, the specimen was unloaded and prepared for a second test. For the subsequent test, the girder was inverted to reverse the loading configuration. Specifically, the flange that originally served as the bottom flange was repositioned at the top, while the flange previously subjected to loading was relocated to the bottom. Following this reconfiguration, the specimen was relabeled as F1803W304-T3.0-ad1.0-S50-2 and reloaded under the same experimental conditions. Additional information regarding the test setup, boundary conditions, loading scheme, and instrumentation can be found in Ref. [29].

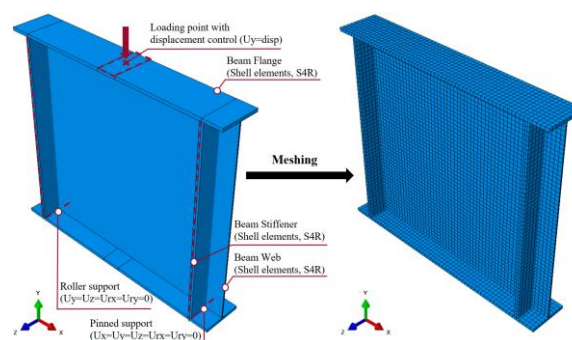
2.3. Summary of numerical modelling approaches

The yield strength, ultimate tensile strength, and elongation obtained from the coupon tests were systematically incorporated into the finite element (FE) modeling framework to ensure an accurate representation of the structural response under various loading conditions. Owing to its proven effectiveness in structural analyses where the plate thickness is significantly smaller than the in-plane dimensions, the S4R element, a four-node, quadrilateral shell element with reduced integration, was adopted for the numerical simulations [32–34]. This element type is particularly well suited for thin-plate applications, as it effectively mitigates shear locking while maintaining high computational efficiency. The nonlinear stress–strain relationship was first fitted using the Ramberg–Osgood model and then discretized into a multi-linear form for implementation in ABAQUS.

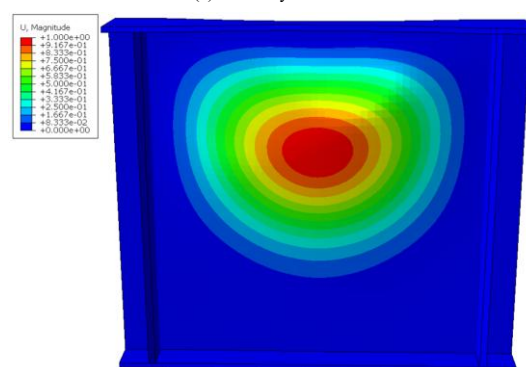
The finite element (FE) models were carefully developed to replicate the experimental loading conditions, allowing for a direct comparison between numerical predictions and experimental results. As illustrated in Fig. 5(a), a vertical displacement was imposed on a designated reference point, which was coupled to the bearing plates through coupling constraints to ensure realistic and consistent load transfer. The bearing plates were modeled as rigid bodies, with

all degrees of freedom constrained to the reference point to enforce a uniform displacement field [35,36]. In addition, Tie constraints were introduced between the girder ends and the stiffened blocks to prevent any relative displacement during loading [37–39]. This modeling approach enabled an accurate representation of the structural response of hybrid-configured girders subjected to localized bearing force.

Using finite element (FE) models, a buckling analysis was performed to assess how initial geometric imperfections affected structural stability [40–42]. The first-order eigenmode, depicted in Fig. 5(b), exhibited a strong agreement with the initial deformations measured during experimental testing, confirming its suitability for imperfection modelling. To integrate these imperfections into the numerical simulations, the *IMPERFECTION keyword was employed, utilizing the first eigenmode derived from the buckling analysis as the basis for the initial geometric imperfection. This mode was scaled to represent realistic deformation amplitudes, ensuring an accurate representation of the structural response under loading conditions [43].



(a) boundary condition and mesh size



(b) First-order buckling mode derived from FE

Fig. 5 FE modelling technique applied in this study [29]

A preliminary assessment of the residual stress indicated that its effect on the resistance of hybrid-configured girders subjected to localized bearing force is negligible. This can be attributed to the fact that the structural response under concentrated forces is predominantly governed by local bearing and web crippling mechanisms, for which the contribution of residual stress is relatively limited. This observation is consistent with the findings reported in previous studies [44,45], which similarly demonstrated that residual stresses exert an insignificant influence on the load-carrying capacity. In light of its marginal effect, the residual stress was therefore neglected in the finite element modeling adopted in this study.

In the present study, the welding configuration, heat input, and geometry of the hybrid and homogeneous girders are essentially identical, only the flange material differs. Consequently, the residual stress distribution in the web, where

patch loading resistance is primarily governed, is expected to be similar in both cases. Since patch loading behaviour is dominated by localized web yielding and crippling rather than global instability, its sensitivity to residual stresses is limited. To further address this concern, a representative critical case was reanalysed with a typical residual stress pattern introduced. The comparison between models with and without residual stresses shows only a marginal difference in the load–displacement response and ultimate capacity.

2.4. Modelling approach validation

To validate the finite element (FE) models, a comprehensive dataset comprising 10 experimental results from the authors' previous study [29] was employed. The validation was conducted by systematically comparing the numerical predictions with the experimental observations in terms of load–

displacement responses, local load-carrying capacity, and failure modes.

As summarized in Table 3, a detailed comparison was performed between the ultimate loads obtained from the experimental tests (F_{test}) and those predicted by the finite element analysis (F_{FE}). The results indicate a mean F_{test}/F_{FE} ratio of 0.988, accompanied by a low coefficient of variation (COV) of 0.015, demonstrating the high level of agreement between the experimental and numerical results. Furthermore, Fig. 6 compares the load–vertical deflection relationships derived from the experimental tests and the FE simulations, revealing a strong correlation over the entire loading range. In addition, Fig. 7 illustrates the comparison between the experimentally observed deformed shapes and those predicted by the FE models. The close agreement in both deformation patterns and failure characteristics further substantiates the capability of the FE models to accurately reproduce the structural behavior of hybrid-configured girders under localized bearing force.

Table 3

Comparison between experimentally and numerically predicted resistances [29]

Specimens	Flange	Specimens	$P_{u, Test}$ (kN)	$P_{u, FEA}$ (kN)	$P_{u, Test} / P_{u, FEA}$
F1803W304-T3.0-ad1.0-S50-1	QN1803	EN 1.4301	99.7	98.8	1.009
F1803W304-T3.0-ad1.0-S50-2	QN1803	EN 1.4301	94.8	98.8	0.96
F1803W304-T3.0-ad1.0-S100-1	QN1803	EN 1.4301	108.6	111.4	0.975
F1803W304-T3.0-ad1.0-S100-2	QN1803	EN 1.4301	110.4	111.4	0.991
F32001W2205-T3.0-ad1.0-S50-1	S32001	EN 1.4462	164.2	164.9	0.996
F32001W2205-T3.0-ad1.0-S50-2	S32001	EN 1.4462	163.6	164.9	0.992
F32001W2205-T3.0-ad1.0-S100-1	S32001	EN 1.4462	173.9	176.8	0.984
F32001W2205-T3.0-ad1.0-S100-2	S32001	EN 1.4462	173.1	176.8	0.979
F32001W2205-T3.0-ad1.5-S100-1	S32001	EN 1.4462	167.9	166.3	1.01
F32001W2205-T3.0-ad1.5-S100-2	S32001	EN 1.4462	164.5	166.3	0.989
Mean					0.988
CoV					0.015

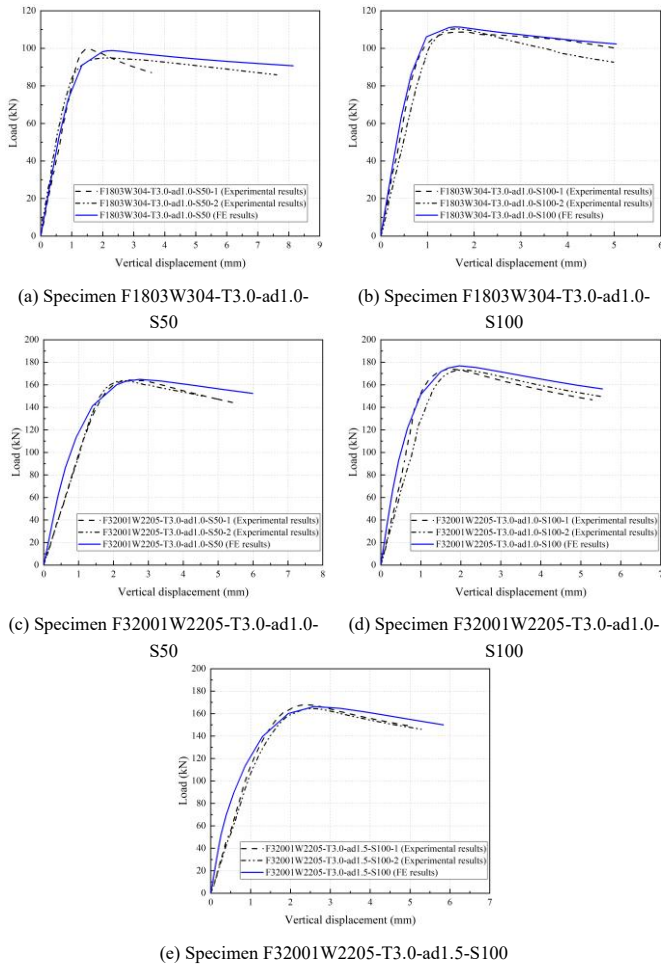


Fig. 6 Load-displacement graphs from the tests and FEA [29]

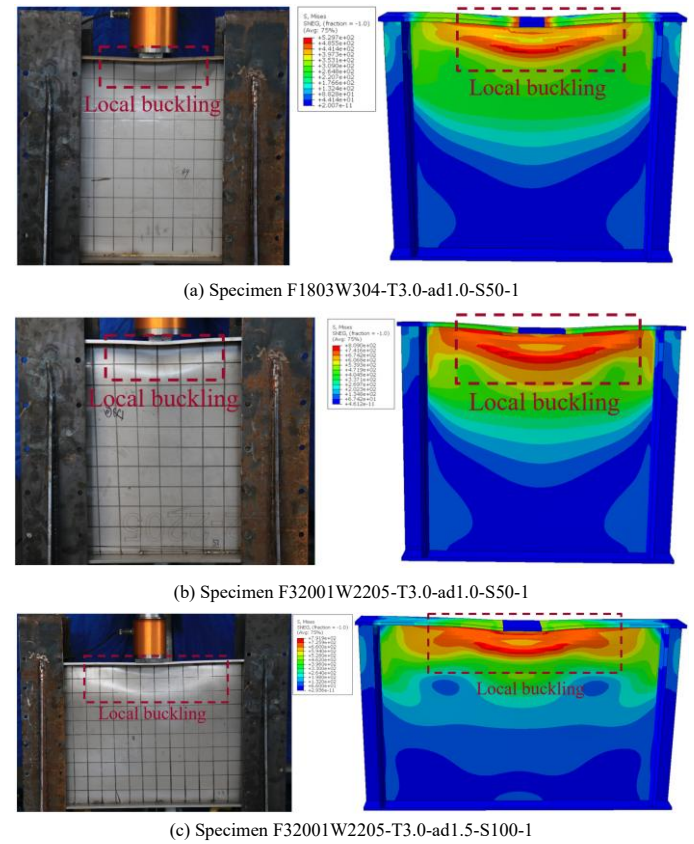


Fig. 7 Comparison of failure modes between the testing and FE models [29]

3. Parametric study

3.1. General

A comprehensive parametric study was carried out using a robust finite

element (FE) model that had been previously developed and extensively validated by the authors, resulting in a total of 1,248 numerical simulations. The material stress–strain relationships adopted in the FE models were derived from the authors' earlier experimental investigations [29]. Key material properties, including yield strength, ultimate tensile strength, and elastic modulus, are systematically summarized in Table 2.

Initially, the localized-loading resistance of hybrid and homogeneous welded girders was evaluated through a thorough comparative analysis. Following that, a parametric analysis was conducted to examine the key variables affecting these hybrid-configured girders' resistance. To assess their individual and combined effects on the behavior of the girder, important parameters such as the bearing width ratio (S_y/h_w), web slenderness ratio (h_w/t_w), local imperfection ratio (w/h_w), and web aspect ratio (a/h_w) were changed.

The ratio of bearing width to web height (S_y/h_w) was varied between 0.1 and 0.4 to examine the influence of load distribution characteristics within the bearing region. The web slenderness ratio (h_w/t_w), ranging from 90.9 to 200.0, was considered to assess the effects of web thickness and associated stability behavior on the load-carrying capacity. The web aspect ratio (a/h_w) was investigated within the range of 1.0 to 2.0 to evaluate its influence on the interaction between local bearing behavior and overall web deformation. In addition, the local imperfection ratio (w/h_w) was varied from 0.0008 to 0.044 to account for the effects of initial geometric imperfections. The adopted ranges of these governing parameters are summarized in Table 4.

Table 4
Details of the parametric analysis

Key parameters	Range
Web aspect ratio (a/h_w)	1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0
Web slenderness ratio (h_w/t_w)	90.9, 94.3, 98.0, 102.0, 106.4, 111.1, 116.3, 122.0, 128.2, 135.1, 142.9, 151.5, 161.3, 172.4, 185.2, 200.0
Local geometric imperfection ratio (w_0/h_w)	0.0008, 0.002, 0.0032, 0.044
Bearing width ratio (S_y/h_w)	0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22, 0.24, 0.26, 0.28, 0.30, 0.32, 0.34, 0.36, 0.38, 0.40

3.2. Comparison between hybrid and homogeneous girders

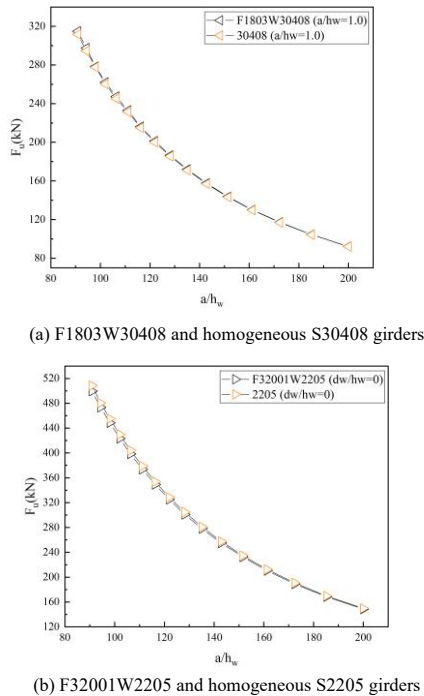


Fig. 8 Comparison between hybrid and homogeneous girders

A comparative evaluation of the local load-carrying capacity is presented in Fig. 8(a) and (b), illustrating the differences in structural performance between hybrid-configured girders and conventional homogeneous girders. Specifically, the analysis examines F1803W304 hybrid-configured girders, which feature flanges made of QN1803 and webs made of EN 1.4301 (S30408), as well as F32001W2205 hybrid-configured girders, constructed with flanges made of S32001 and webs made of EN 1.4301 (S30408). These are compared

to homogeneous girders composed entirely of EN 1.4462 (S2205). The objective is to assess whether hybrid-configured girders can achieve localized-loading resistance comparable to that of homogeneous girders while optimizing material use.

The results demonstrate that the local load-carrying capacity of the F1803W304 and F32001W2205 hybrid-configured girders is comparable to that of homogeneous EN 1.4301 (S30408) and EN 1.4462 (S2205) girders, respectively. This indicates that the use of QN1803 and S32001 as flange materials does not adversely affect the structural performance under localized bearing force conditions. Moreover, given the higher strength of QN1803 compared to EN 1.4301 (S30408), the moment resistance of hybrid-configured girders is expected to exceed that of homogeneous girders. These findings underscore the structural efficiency of hybrid-configured girders, which capitalize on the mechanical advantages of different materials to enhance performance while potentially reducing material costs and weight.

Both hybrid and homogeneous girders exhibit the same dominant failure modes under patch loading, characterized by initial web yielding followed by localized buckling or crushing. This indicates that the patch loading response is primarily governed by localized web behavior, including web crippling, local plastic deformation, and instability. In this loading scenario, the web acts as the principal load-resisting component. The flange mainly serves as a load-introduction element that transfers and distributes the applied patch load into the web. Moreover, the load transfer path from the patch load to the web is essentially identical in both hybrid and homogeneous girders. Although the high-strength flange in the hybrid configuration improves local stiffness, it does not fundamentally alter the deformation pattern, stress distribution, or governing failure mechanism of the web. As a result, both girder types exhibit comparable structural performance under patch loading.

3.3. Effect of local geometrical imperfection ratio (w/h_w)

The effect of the local geometric imperfection ratio (w_0/h_w) on the ultimate local load-carrying capacity of the F1803W304 and F32001W2205 hybrid-configured girders is illustrated in Figs. 9(a) and (b). Values of w_0/h_w ranging from 0.0008 to 0.0044 were considered for each web configuration. The results indicate that the variations in local load-carrying capacity induced by different imperfection amplitudes remain consistently below 1% for all investigated specimens. This limited sensitivity suggests that the localized bearing response of stainless steel plate girders is largely governed by material yielding and web crippling mechanisms, with initial local geometric imperfections playing a secondary role. In view of the negligible influence observed and to ensure numerical efficiency and consistency, a local geometric imperfection ratio of $w_0/h_w = 0.0008$ was therefore adopted in the subsequent parametric analyses.

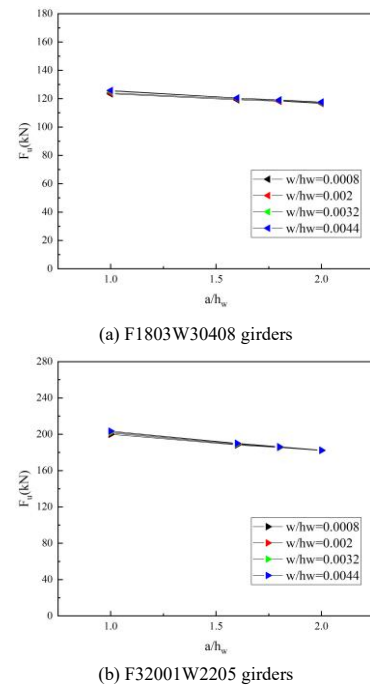


Fig. 9 Effect of initial imperfection on the ultimate strength

3.4. Effect of web aspect ratio (a/h_w)

The influence of the web aspect ratio (a/h_w) on the local load-carrying

capacity of the F1803W304 and F32001W2205 hybrid-configured girders is illustrated in Figs. 10(a) and (b), respectively. The parametric analysis covered a/h_w values ranging from 1.0 to 2.0 with an increment of 0.1. Typical failure modes observed in selected girder specimens are presented in Figs. 11 and 12. The results demonstrate that, for a given web aspect ratio, an increase in the bearing width ratio (S_s/h_w) leads to a pronounced enhancement in local load-carrying capacity. This trend reflects the beneficial effect of load dispersion over a wider bearing region, which delays the onset of localized web crippling. For instance, when $a/h_w = 1.0$, increasing the S_s/h_w ratio from 0.10 to 0.38 results in an increase in the ultimate local load-carrying capacity of 33.7% for the F1803W304 hybrid-configured girders and 31.7% for the F32001W2205 hybrid-configured girders.

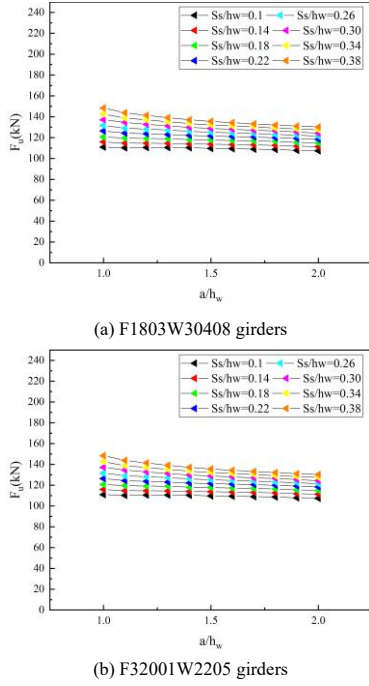


Fig. 10 Effect of a/h_w on the ultimate strength

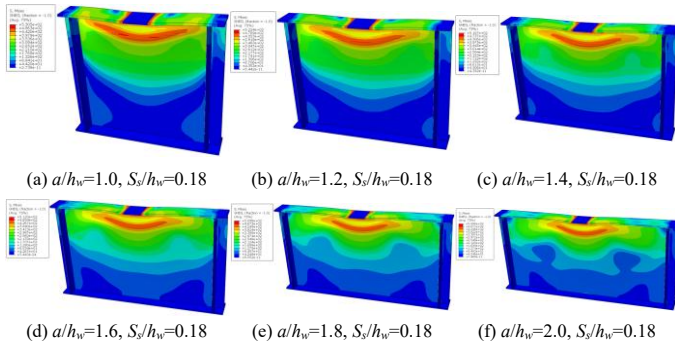


Fig. 11 Typical failure modes for F1803W30408 specimens with varying a/h_w

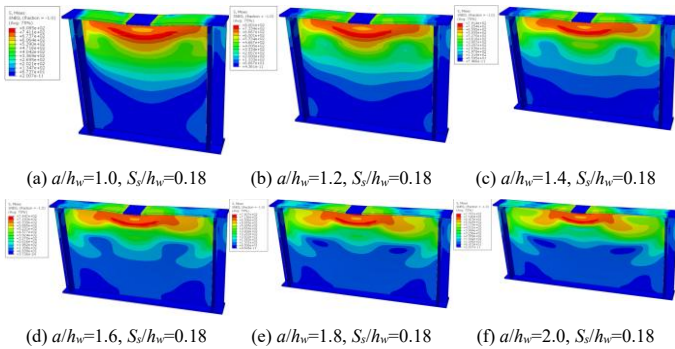


Fig. 12 Typical failure modes for F32001W2205 specimens with varying a/h_w

Furthermore, the local load-carrying capacity exhibits a decreasing trend as the web aspect ratio (a/h_w) increases from 1.0 to 2.0, with this effect being more

pronounced in specimens characterized by lower bearing width ratios (S_s/h_w). Specifically, in F1803W304 hybrid-configured girders, increasing a/h_w from 1.0 to 2.0 results in localized-loading resistance reductions of 3.15%, 4.78%, and 1.22% for S_s/h_w ratios of 0.1, 0.18, and 0.38, respectively. Similarly, in F32001W2205 hybrid-configured girders, the corresponding reductions were 6.56%, 8.34%, and 14.80%. These results underscore the substantial impact of the web aspect ratio on localized-loading resistance, emphasizing the importance of incorporating this parameter in the formulation of new design equations.

3.5. Effect of web slenderness (h_w/t_w)

The influence of the web slenderness ratio (h_w/t_w) on the local load-carrying capacity of the F1803W304 and F32001W2205 hybrid-configured girders is presented in Figs. 13(a) and (b). In this parametric analysis, the web aspect ratio (a/h_w) was systematically varied from 1.0 to 2.0 in increments of 0.2.

The findings reveal that for fixed values of h_w/t_w and increasing a/h_w leads to a pronounced reduction in the member's capacity under localized bearing force. In F1803W304 hybrid-configured girders, increasing the a/h_w ratio from 1.0 to 2.0 leads to a strength reduction of 13.4% for $h_w/t_w = 90.9$ and 5.1% for $h_w/t_w = 200.0$. Similarly, for F32001W2205 hybrid-configured girders, the same increase in a/h_w causes strength reductions of 19.9% and 9.3% for h_w/t_w values of 90.9 and 200.0, respectively.

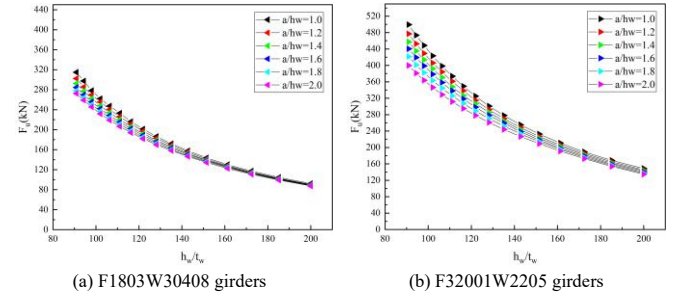


Fig. 13 Effect of h_w/t_w on the ultimate strength

The results also demonstrate that a marked decline in localized-loading capacity was observed as h_w/t_w increased from 90.9 to 200.0. In F1803W304 hybrid-configured girders with fixed a/h_w values of 1.0, 1.6, and 2.0, the reductions are 70.7%, 68.6%, and 67.9%, respectively, while in F32001W2205 hybrid-configured girders, the corresponding reductions are 70.2%, 68.2%, and 66.3%. In addition, as illustrated in Figs. 14 and 15, increasing web slenderness ratios result in more pronounced local buckling behavior, underscoring the critical role of web slenderness in governing the local load-carrying capacity of hybrid configured girders.

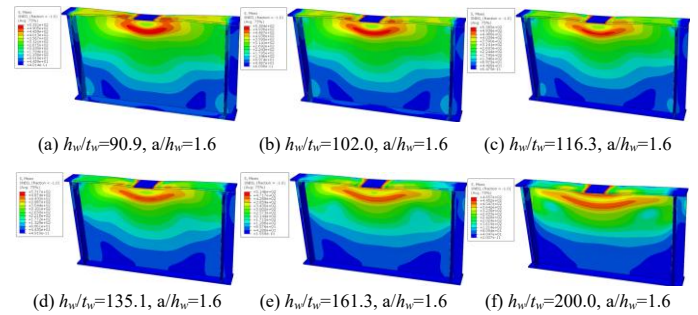


Fig. 14 Typical failure modes for F1803W30408 specimens with varying h_w/t_w

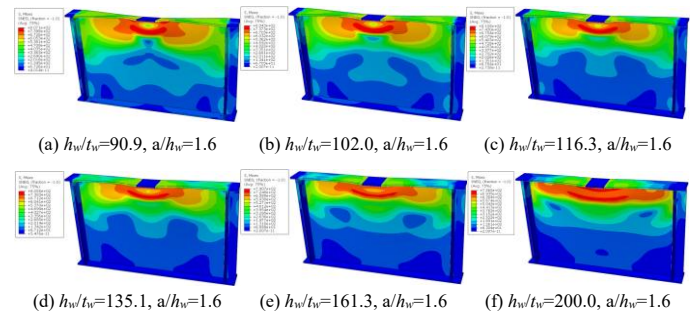


Fig. 15 Typical failure modes for F32001W2205 specimens with varying h_w/t_w

3.6. Effect of bearing width ratio (S_s/h_w)

The role of the bearing width-to-web depth ratio (S_s/h_w) in influencing localized-load resistance of F1803W304 and F32001W2205 hybrid-configured girders is presented in Figs. 16(a) and (b), with representative failure modes shown in Figs. 17 and 18. The results indicate a consistent increase in localized-loading resistance as the bearing width ratio (S_s/h_w) increases from 0.1 to 0.38. These observations are consistent with the trends identified in Section 3.5, which demonstrated that increasing h_w/t_w leads to a substantial drop in the peak localized load-bearing capacity. For F1803W304 hybrid-configured girders with an h_w/t_w ratio of 142.9, increasing S_s/h_w ranging from 0.1 to 0.38 with step sizes of 0.04 leads to corresponding resistance gains of 5.0%, 10.6%, 15.4%, 20.7%, 26.3%, 31.7%, and 37.4%. Similarly, for F32001W2205 hybrid-configured girders under the same conditions, the increases are 5.3%, 10.5%, 15.4%, 20.4%, 25.2%, 30.2%, and 35.3%. These results highlight the critical role of S_s/h_w in local bearing capacity.

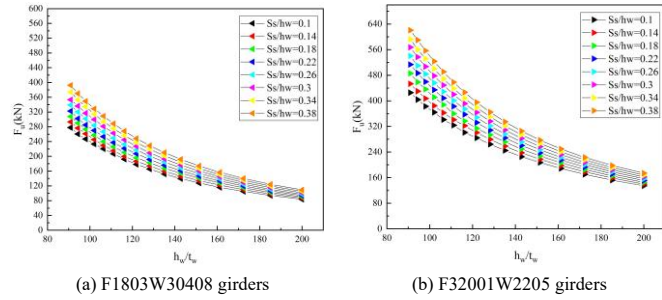


Fig. 16 Effect of S_s/h_w on the ultimate strength

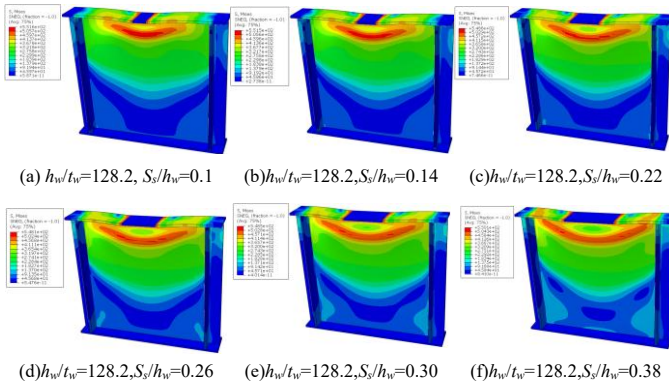


Fig. 17 Typical failure modes for F1803W30408 specimens with varying S_s/h_w

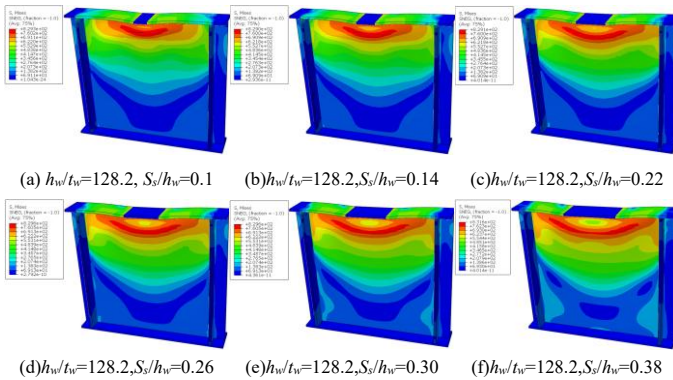


Fig. 18 Typical failure modes for F32001W2205 specimens with varying S_s/h_w

The comparative analyses presented above clearly demonstrate that the bearing width ratio, web aspect ratio, and web slenderness exert a dominant influence on the local load-carrying capacity of hybrid-configured girders. These parameters govern the load transfer mechanisms and stability characteristics of the web, and therefore play a critical role in determining the structural performance of such members. Consequently, they must be explicitly incorporated into the proposed design formulations developed in this study to ensure both predictive accuracy and engineering reliability. By contrast, the effect of initial geometric imperfections was shown to be negligible within the investigated range. This finding indicates that their influence on local load-

carrying capacity is secondary and may be reasonably neglected in the development of the new design recommendations, thereby enabling a simplified yet robust design framework.

4. Existing design rules for homogeneous girders

4.1. General

As previously mentioned, the design methods for hybrid stainless steel girders under localized forces are not currently available. The current design criteria outlined in GB 50017 [26], EN 1993-1-5 [27], and ANSI/AISC 360-22 [28] were generated with the assumption of homogeneous girders. These codes do not account for the unique characteristics and performance variations inherent in hybrid-configured girders, which combine different material grades in their construction. This section will provide a summary and discussion of the current design criteria, as outlined follows:

4.2. EN 1993-1-5 [27]

The current version of EN 1993-1-5 [27] provides design provisions for evaluating the resistance of homogeneous steel girders under three distinct loading conditions, with particular emphasis on the effects of plate behavior. A key distinction between EN 1993-1-5 [27] and GB 50017 [26] lies in the treatment of strength reductions associated with web buckling. EN 1993-1-5 [27] explicitly accounts for the influence of web instability on the load-carrying capacity by incorporating reduction factors that reflect the susceptibility of slender webs to local buckling. In contrast, GB 50017 [26] adopts a different design philosophy, in which the effects of web buckling are treated in a less explicit manner. This fundamental difference may result in discrepancies in the predicted resistance of girders, particularly for members with relatively high web slenderness ratios, where web instability plays a governing role in the overall structural response.

The design strength associated with failure under localized bearing force ($P_{u,EN}$) is determined by considering several critical parameters that influence the structural behavior of hybrid-configured girders. These parameters include the yield strength of the web (f_{yw}), the web thickness (t_w), the effective length (L_{eff}), and the partial safety factor (γ_{M1}). The interaction between these factors governs the localized-loading resistance. The mathematical formulation of this relationship is provided in Eqs. (1)-(7)

$$P_{u,EN} = \frac{f_{yw} L_{eff} t_w}{\gamma_{M1}} \quad (1)$$

$$L_y = s_s + 2t_f(1 + \sqrt{m_1 + m_2}) \leq a \quad (2)$$

$$m_1 = f_{yf} b_f / f_{yw} t_w \quad (3)$$

$$m_2 = 0.02(h_w/t_f)^2, \text{ if } \lambda_F > 0.5; m_2 = 0, \text{ if } \lambda_F \leq 0.5 \quad (4)$$

$$\chi_F = \frac{0.5}{\lambda_F} \leq 1.0 \quad (5)$$

$$\lambda_F = \sqrt{\frac{I_y t_w f_{yw}}{F_{cr}}}; F_{cr} = 0.9 k_F E \frac{t_w^3}{h_w} \quad (6)$$

$$k_F = 6 + 2\left(\frac{h_w}{a}\right)^2 \quad (7)$$

4.3. ANSI/AISC 360-22 [28]

In current practice, the evaluation of localized bearing resistance in homogeneous mild steel members is primarily governed by the design framework established in ANSI/AISC 360-22 [28]. The specification adopts a design philosophy that is largely in line with the principles underlying EN 1993-1-5 [27], thereby ensuring a reasonable level of consistency across major international steel design codes. Despite this general alignment, AISC 360-22 [28] does not explicitly incorporate the effect of web aspect ratio in the

formulation of local resistance. The omission of this geometric parameter limits the ability of the specification to capture the influence of web configuration on localized failure mechanisms

This limitation may result in discrepancies in strength predictions, particularly for members with varying web geometries. According to AISC 360-22 [28], the ultimate resistance of homogeneous mild steel members subjected to localized bearing force is evaluated using Eqs. (8)–(10):

(1) Transverse loading is applied at a distance $\geq d/2$ from the girder's end

$$P_{u,AISC} = 0.8t_w^2 \left[1 + 3 \left(\frac{S_s}{d} \right) \left(\frac{t_w}{t_f} \right)^{1.5} \right] \sqrt{\frac{E f_{yw} t_f}{t_w}} \quad (8)$$

(2) Transverse loading is applied at a distance $< d/2$ from the girder's end:

$$P_{u,AISC} = 0.4t_w^2 \left[1 + 3 \left(\frac{S_s}{d} \right) \left(\frac{t_w}{t_f} \right)^{1.5} \right] \sqrt{\frac{E f_{yw} t_f}{t_w}}; \text{ for } S_s / d \leq 0.2 \quad (9)$$

$$P_{u,AISC} = 0.4t_w^2 \left[1 + \left(\frac{4S_s}{d} - 0.2 \right) \left(\frac{t_w}{t_f} \right)^{1.5} \right] \sqrt{\frac{E f_{yw} t_f}{t_w}}; \text{ for } S_s / d > 0.2 \quad (10)$$

4.4. GB 50017 [26]

The existing provisions in GB 50017 [26] define design criteria for assessing the resistance of structural members subjected to localized bearing actions. Nevertheless, the scope of this standard is limited to members fabricated from homogeneous mild steel, without explicit consideration of the distinct mechanical properties and load-transfer mechanisms associated with stainless steel or hybrid structural systems. Consequently, the applicability of GB 50017 [26] to girders with hybrid configurations remains questionable. This limitation underscores the necessity for updated or supplementary design provisions that can accurately reflect the unique characteristics of advanced materials, ensuring reliable and efficient structural performance assessments.

To evaluate the resistance of homogeneous mild steel girders subjected to localized forces, the following Eqs. (11)–(12) can be applied:

$$P_{u,GB} = \frac{f_{yw} t_w l_z}{\Psi} \quad (11)$$

$$l_z = S_s + 5t_f + 2h_R \quad (12)$$

4.5. Evaluation of the existing design standards

As summarized in Table 5, a comprehensive comparative assessment was conducted to evaluate the accuracy of existing design provisions for homogeneous girders. The results of the parametric study were systematically compared with the strength predictions obtained using widely adopted design standards, including GB 50017 [26], EN 1993-1-5 [27], and ANSI/AISC 360-22 [28].

Table 5

Comparison of FEA results with predicted values by the existing standards

Material		GB 50017 [26]	EN 1993- 1-5 [27]	ANSI/AISC 360-22 [28]
		$F_{u,GB} / F_{u,FE}$	$F_{u,EN} / F_{u,FE}$	$F_{u,AISC} / F_{u,FE}$
F1803W304	Mean	1.033	0.587	0.850
	COV	0.228	0.109	0.069
F32001W2205	Mean	1.294	0.519	0.755
	COV	0.230	0.116	0.080

For EN 1993-1-5 [27], the average strength ratio ($F_{u,EN}/F_{u,FE}$) is 0.587 and 0.519 for F1803W304 and F32001W2205 hybrid-configured girders, respectively, yielding coefficient of variation (COV) values of 0.109 and 0.116. Figs. 19(a) and (b) further compare these predictions with FEA results, highlighting that EN 1993-1-5 [27] provides notably conservative estimates. This suggests that the current provisions may underestimate the localized-loading resistance of hybrid-configured girders, potentially leading to inefficient material utilization and overly cautious design recommendations.

Future revisions to EN 1993-1-5 [27] may be necessary to enhance its predictive accuracy.

For ANSI/AISC 360-22 [28], the average strength ratio ($F_{u,AISC}/F_{u,FE}$) is 0.850 and 0.755, with COVs of 0.069 and 0.080 for F1803W304 and F32001W2205 hybrid-configured girders, respectively. As illustrated in Figs. 19(c) and (d), ANSI/AISC 360-22 [28] consistently predicts localized-loading resistance with an average conservatism of 19.8%. Compared to both GB 50017 [26] and EN 1993-1-5 [27], ANSI/AISC 360-22 [28] demonstrates improved predictive accuracy, making it a more reliable reference for assessing the localized-loading resistance of hybrid-configured girders. The different conservatism of EN 1993-1-5 [27] and AISC 360-22 [28] mainly stems from their treatment of web instability and parameter sensitivity. EN 1993-1-5 [27] includes web buckling reduction linked to web slenderness and strength, leading to increased conservatism for higher web grades and instability-controlled regimes. In contrast, AISC 360-22 [28] does not explicitly consider geometric parameters such as the load length-to-web depth ratio (a/h_w), resulting in reduced sensitivity to web grade and parameter regime. This explains the observed differences in conservatism and highlights directions for future code improvement.

For GB 50017 [26], the mean strength ratio ($F_{u,GB}/F_{u,FE}$) is 1.033 and 1.294, with corresponding COVs of 0.228 and 0.230 for F1803W304 and F32001W2205 hybrid-configured girders, respectively. Figs. 19(e) and (f) provide a comparative assessment, revealing that GB 50017 [26] overestimates localized-loading resistance, with strength predictions averaging 16.4% higher than those derived from FEA simulations. These findings indicate that the current GB 50017 [26] provisions are unconservative and may require modifications to improve their reliability in predicting the performance of hybrid-configured girders under localized bearing force. The approximately 16% unconservative prediction mainly arises from the simplified assumptions adopted in GB 50017 [26] for patch loading resistance. The code provisions [26] are largely based on empirical formulations calibrated for conventional homogeneous mild steel sections. In contrast, the specimens investigated in this study are made of stainless steel, which exhibits distinct material characteristics, including pronounced strain hardening and different post-yield behavior.

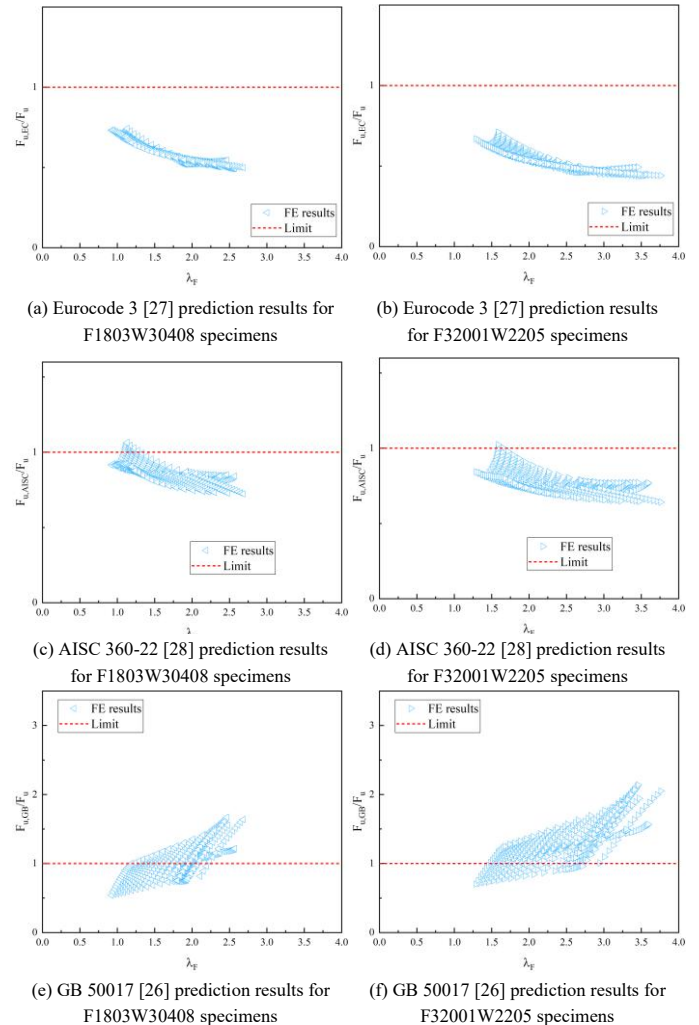


Fig. 19 Comparison between numerical results with design strength derived from current design methods [26-28]

It should be noted that a brief FE uncertainty assessment has been included by examining the sensitivity of the predicted patch loading capacity to (i) mesh refinement, (ii) initial geometric imperfection amplitude, and (iii) material property variability within reasonable bounds. The comparison confirms that the conclusion regarding the unconservatism of GB 50017 [26] remains valid within this FE uncertainty range.

According to the comparative results, the current design requirements are unreliable in their capacity to anticipate the hybrid-configured girders' localized-loading resistance. Substantial discrepancies were identified between the parametric study outcomes and the strength values estimated by existing codes, highlighting the inherent limitations of current design standards.

5. New design proposals for hybrid-configured girders

5.1. General

In this study, a modified coefficient (ξ) was introduced into the existing design formulations to improve the accuracy of local load-carrying capacity predictions for hybrid-configured girders. This coefficient is intended to capture the distinct mechanical response arising from the hybrid material configuration, thereby addressing inherent limitations in current design provisions developed for homogeneous members. Based on this modification, two simplified design approaches were subsequently proposed, specifically tailored for hybrid-configured girders. These approaches are formulated on the basis of the design concepts adopted in EN 1993-1-5 [27] and ANSI/AISC 360-22 [28], and provide refined expressions for evaluating local load-carrying capacity while explicitly accounting for the unique structural characteristics of hybrid-configured girders. In earlier research, the authors [19] used a similar methodology to develop improved design techniques for welded girders.

The novelty of this study lies not merely in introducing a modified coefficient, but in identifying and quantifying the key mechanical differences between hybrid and homogeneous girders under patch loading. Existing patch loading formulations were developed for homogeneous sections and implicitly assume uniform material behavior across the flange and web. In hybrid girders, however, differences in σ - ϵ nonlinearity and strain hardening between the flange and web lead to altered load transfer, stress redistribution, and plastic zone development near the load introduction region. The coefficient ξ was therefore introduced to account for these hybrid-specific mechanisms in a rational manner. Each term in ξ represents a distinct physical contribution: (i) the relative flange-web material and stiffness mismatch, governing load sharing and effective load spread into the web; (ii) the web-dominated local failure mechanism, which controls patch loading resistance; and (iii) the influence of material nonlinearity and post-yield redistribution on the ultimate capacity. The form of ξ was thus derived based on observed mechanical behavior rather than purely empirical fitting.

5.2. Modified ANSI/AISC 360-22 [28]

Similarly, the proposed calculation methods for evaluating the localized-loading resistance ($F_{u, AISC-M}$) of F1803W304 and F32001W2205 hybrid-configured girders are derived from Eqs. (13) and (14), based on ANSI/AISC 360-22 [28]. To improve the accuracy of design predictions for S30408 and S2205 webs, a modified coefficient (ξ) was introduced. This coefficient accounts for key parameters, including S_s/h_w , a/h_w and h_w/t_w , and can be determined using Eqs. (13)–(14):

$$F_{u, AISC-M} = \xi \left(\frac{S_s}{h_w}, \frac{a}{h_w}, \frac{h_w}{t_w} \right) \frac{f_{yw} L_{eff} t_w}{\gamma_{M1}} \quad (13)$$

$$\xi \left(\frac{S_s}{h_w}, \frac{a}{h_w}, \frac{h_w}{t_w} \right) = \begin{cases} 0.6949 \times \left[1 + 0.2951 \left(\frac{S_s}{h_w} \right)^{1.2122} \right] \times \left[1 - 0.1752 \left(\frac{a}{h_w} \right)^{0.6024} \right] \times \left[1 + 0.0731 \left(\frac{h_w}{t_w} \right)^{0.539} \right] & \text{(For F1803W30408)} \\ 0.3348 \times \left[1 + 0.2582 \left(\frac{S_s}{h_w} \right)^{0.5839} \right] \times \left[1 - 0.2865 \left(\frac{a}{h_w} \right)^{0.4255} \right] \times \left[1 + 0.6810 \left(\frac{h_w}{t_w} \right)^{0.372} \right] & \text{(For F32001W2205)} \end{cases} \quad (14)$$

Figs. 20(a) and (b) present a comparison between the localized loading capacities predicted using the modified ANSI/AISC 360-22 design approach and those obtained from the parametric finite element investigation. As summarized in Table 6, the mean ratios of the finite element results (FEM) to the corresponding design predictions for the F1803W304 and F32001W2205 hybrid-configured girders are 1.001 and 1.002, respectively. The associated coefficients of variation (COVs) are 0.023 and 0.025, indicating a high level of consistency and low scatter. These results demonstrate that the modified ANSI/AISC 360-22 design equations provide accurate and reliable predictions

of local load-carrying capacity for hybrid stainless steel girders, thereby confirming their suitability for practical engineering design applications.

Table 6

Comparison of FEA results with predicted values by the proposed methods

Material		Modified EN 1993-1-5	Modified ANSI/AISC 360-22
		$F_{u, EN} / F_{u, FE}$	$F_{u, AISC} / F_{u, FE}$
F1803W304	Mean	1.000	1.001
	COV	0.025	0.023
F32001W2205	Mean	1.000	1.002
	COV	0.029	0.025

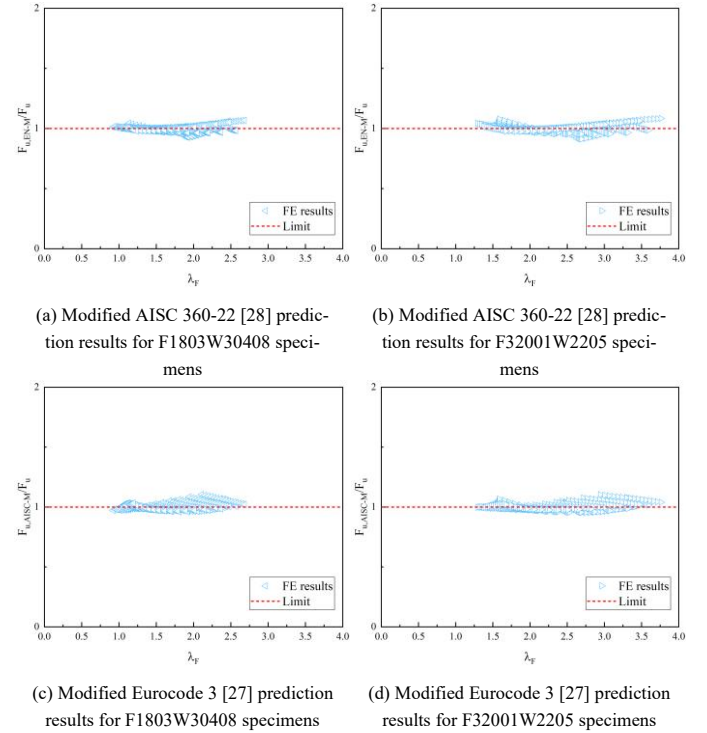


Fig. 20 Comparison between numerical results with design strength derived from new design methods

5.3. Modified EN 1993-1-5 [27]

The proposed calculation methods for evaluating the local load-carrying capacity ($F_{u, EN-M}$) are presented in Eqs. (15)–(16), which are developed through targeted adaptations of the EN 1993-1-5 design framework [24]. To improve the accuracy of resistance predictions for hybrid-configured girders, a modified coefficient (ξ) is introduced in the present study, specifically calibrated for the F1803W304 and F32001W2205 configurations. This coefficient is intended to account for the distinct material properties and mechanical behavior associated with the hybrid stainless steel composition. It is formulated as a function of key governing parameters, including the bearing width ratio (S_s/h_w), web aspect ratio (a/h_w) and web slenderness ratio (h_w/t_w). The modified coefficient ξ is determined using Eqs. (15)–(16):

$$F_{u, EN-M} = \xi \left(\frac{S_s}{h_w}, \frac{a}{h_w}, \frac{h_w}{t_w} \right) \frac{f_{yw} L_{eff} t_w}{\gamma_{M1}} \quad (15)$$

$$\xi \left(\frac{S_s}{h_w}, \frac{a}{h_w}, \frac{h_w}{t_w} \right) = \begin{cases} 0.6268 \times \left[1 + 0.4200 \left(\frac{S_s}{h_w} \right)^{1.4857} \right] \times \left[1 - 0.0012 \left(\frac{a}{h_w} \right)^{2.8587} \right] \times \left[1 + 0.0447 \left(\frac{h_w}{t_w} \right)^{0.7259} \right] & \text{(For F1803W30408)} \\ 0.5914 \times \left[1 + 0.3006 \left(\frac{S_s}{h_w} \right)^{0.9936} \right] \times \left[1 - 0.0139 \left(\frac{a}{h_w} \right)^{2.2613} \right] \times \left[1 + 0.0677 \left(\frac{h_w}{t_w} \right)^{0.7} \right] & \text{(For F32001W2205)} \end{cases} \quad (16)$$

As illustrated in Figs. 20(c) and (d), a comparative assessment was performed between the localized loading capacities predicted using the modified EN 1993-1-5 equations and those obtained from the parametric finite element analyses of the F1803W304 and F32001W2205 hybrid-configured girders. This comparison was conducted to evaluate the accuracy of the revised equations in capturing the local load-carrying capacity of these stainless steel

girders.

As summarized in Table 6, the mean ratios of the finite element results to the corresponding design predictions are equal to 1.000 for both the F1803W304 and F32001W2205 configurations. The associated coefficients of variation (COVs) are 0.025 and 0.029, respectively, indicating low scatter and a high level of agreement. These findings confirm that the revised EN 1993-1-5-based design equations provide reliable and precise estimates of local load-carrying capacity for hybrid stainless steel girders.

6. Concluding remarks and limitations

A novel generation of hybrid stainless steel girders has been used in marine structures recently. This study introduces new simplified design methods for assessing the resistance of hybrid stainless steel girders under localized bearing force, expanding on the authors' earlier experimental research. A comprehensive investigation was carried out, involving 1248 finite element (FE) simulations. The principal findings of this study are summarized as follows:

(1) A finite element (FE) model, previously developed and rigorously validated by the authors, was utilized to perform a comprehensive parametric investigation. The study focused on evaluating the influence of critical parameters, including the bearing width ratio, web aspect ratio, web slenderness, and local geometric deformations, on the structural behavior of the tested girders.

(2) The parametric study results reveal that the localized-loading resistance of hybrid stainless steel girders is primarily influenced by three key factors: the web aspect ratio, web slenderness ratio, and bearing width ratio. The analysis demonstrates a consistent enhancement in resistance as the bearing width ratio (S_f/h_w) increases from 0.1 to 0.4. Conversely, a notable decline in resistance is

observed when the web slenderness (h_w/t_w) rises from 90.9 to 200.0. In comparison, the web aspect ratio (a/h_w), ranging from 1.0 to 2.0) exhibits a relatively limited effect on resistance.

(3) The comparison between hybrid and homogeneous girders demonstrates that the use of QN1803 flanges does not adversely affect performance under localized bearing force. Furthermore, owing to the higher strength of QN1803 relative to EN 1.4301 (S30408), hybrid-configured girders are expected to achieve greater moment resistance compared to their homogeneous counterparts.

(4) The comparison between the predicted strength values and numerical results revealed notable inconsistencies with existing design codes. Specifically, the predictions based on GB 50017 (2017) were unconservative, underestimating the strength by an average of 16.4%. In contrast, EN 1993-1-5 (2006) and ANSI/AISC 360-22 (2022) yielded conservative estimates, overestimating the strength by 44.7% and 19.8%, respectively. These substantial discrepancies between the parametric study outcomes and code-based predictions underscore the limitations of current design standards in accurately assessing the resistance of such hybrid-configured girders.

(5) New simplified design recommendations were formulated for determining the resistance of hybrid-configured girders. A modified coefficient (ζ) was introduced, built upon the framework of existing design equations. The newly proposed methods enhance the accuracy of predicting the localized-loading resistance of such hybrid-configured girders.

(6) The present study focuses on internal one-flange (IOF) midspan patch loading, which represents a fundamental and widely used reference case for isolating web-dominated mechanisms. Other loading scenarios are identified as important extensions beyond the current scope.

References

- [1] Feng, R., Yang, F., Shao, Y., Roy, K., Lim, J., Chen, B. (2024). Experimental study on high-cycle fatigue behaviour of butt welds made of corroded AISI 304 stainless steel and Q460 high-strength steel, *Structures* 62, 106141.
- [2] Veljkovic, M., & Johansson, B. (2004). Design of hybrid steel girders. *Journal of Constructional Steel Research*, 60(3-5), 535-547.
- [3] Graciano, C. (2015). Patch loading resistance of longitudinally stiffened girders—A systematic review. *Thin-Walled Structures*, 95, 1-6.
- [4] Graciano, C., & Johansson, B. (2003). Resistance of longitudinally stiffened I-girders subjected to concentrated loads. *Journal of Constructional steel research*, 59(5), 561-586.
- [5] Kovacevic, S., & Markovic, N. (2020). Experimental study on the influence of patch load length on steel plate girders. *Thin-Walled Structures*, 151, 106733.
- [6] Dos Santos, G. B., Gardner, L., & Kucukler, M. (2018). Experimental and numerical study of stainless steel I-sections under concentrated internal one-flange and internal two-flange loading. *Engineering Structures*, 175, 355-370.
- [7] Dos Santos, G. B., & Gardner, L. (2020). Design recommendations for stainless steel I-sections under concentrated transverse loading. *Engineering Structures*, 204, 109810.
- [8] Graciano, C., Loaiza, N., & Casanova, E. (2019). Resistance of slender austenitic stainless steel I-girders subjected to patch loading. *Structures*, 20, 924-934.
- [9] Azizinamini, A., Hash, J. B., Yakel, A. J., & Farimani, R. (2007). Shear capacity of hybrid plate girders. *Journal of Bridge Engineering*, 12(5), 535-543.
- [10] Shokouhian, M., & Shi, Y. (2015). Flexural strength of hybrid steel I-beams based on slenderness. *Engineering Structures*, 93, 114-128.
- [11] Chacón, R., Bock, M., & Real, E. (2011). Longitudinally stiffened hybrid steel plate girders subjected to patch loading. *Journal of Constructional Steel Research*, 67(9), 1310-1324.
- [12] Chacón, R., Mirambell, E., & Real, E. (2010). Hybrid steel plate girders subjected to patch loading. Part 1: Numerical study. *Journal of Constructional Steel Research*, 66(5), 695-708.
- [13] Wang, Y., Chen, B., Hu, S., Ye, Q., Sun, Y., Li, B., & Zhao, H. (2026). Testing, simulation and design of hybrid stainless steel girders under shear. *Journal of Constructional Steel Research*, 236, 110000.
- [14] Lalthazuala, R., & Singh, K. D. (2019). Structural performance of hybrid stainless steel plate girders under shear. *Thin-Walled Structures*, 143, 106214.
- [15] Lalthazuala, R., & Singh, K. D. (2019). Investigations on structural performance of hybrid stainless steel I-beams based on slenderness. *Thin-Walled Structures*, 137, 197-212.
- [16] Lalthazuala, R., & Singh, K. D. (2020). Structural behaviour of hybrid stainless steel stub columns under axial compression. *Structures*, 27, 128-140.
- [17] Bock, M., Gkantou, M., Theofanous, M., Afshan, S., & Yuan, H. (2023). Ultimate behaviour of hybrid stainless steel cross-sections. *Journal of Constructional Steel Research*, 210, 108081.
- [18] Chen, B., Dai, Y., Wang, Y., Wang, Y., Song, Y., Luo, L., & Hai, L. (2025). Patch-loading resistance of QN1803 and S32001 high-strength stainless steel plate girders: Experimental study and numerical simulation. *Thin-Walled Structures*, 206, 112681.
- [19] Dai, Y., Chen, B., Wang, Y., Ye, Q., Luo, L., Li, B., & Hai, L. (2025). Parametric study and new design recommendations for high-strength stainless steel plate girders under patch loading. *Structures*, 71, 108064.
- [20] Chen, B., Wang, Y., Luo, L., Liu, J., Huang, C., Zhang, T., & Hai, L. (2025). An experimental study on the reduced resistance of perforated S32001 high-strength stainless steel girder under patch loading. *Engineering Structures*, 327, 119672.
- [21] Chen, B., Wang, Y., Xing, Z., Lim, J. B., & Hai, L. (2024). Material properties and shear behaviour of QN1803 high-strength stainless steel plate girders. *Engineering Structures*, 301, 117209.
- [22] Chen, B., Wang, Y., Xu, D., Wang, Z., Liu, X., & Lim, J. B. (2023). An experimental study on shear resistance of austenitic and duplex stainless steel plate girders with perforated webs. *Engineering Structures*, 295, 116823.
- [23] Chen, B., Wang, Y., Xu, D., Yuan, H., Yan, L., (2023). Finite element analysis and proposed design rules for 304D high-strength stainless steel I-shaped members in shear, *Journal of Constructional Steel Research* 204, 107861
- [24] Ye, Q., Nie, H., Chen, B., Wang, Y., Lu, P., Dai, P., & Hai, L. (2025). Local buckling behaviour of welded stainless steel I-beams with perforated webs. *Thin-Walled Structures*, 212, 113201.
- [25] Wang, Y., Chen, B., Dai, P., Chen, Y., Sun, Y., Song, Y., & Lim, J. B. (2025). Localized loading behaviour of perforated QN1803 high-strength stainless steel welded plate girders. *Journal of Constructional Steel Research*, 235, 109907.
- [26] GB 50017-2017, Standard for design of steel structures, China Planning Press, Beijing, 2017 (In Chinese).
- [27] EN 1993-1-5:2006, Eurocode 3: Design of Steel Structures – Part 1-5: Plated structural Elements, European Committee for Standardization (CEN), Brussels, 2006
- [28] ANSI/AISC 360-22, Specification for Structural Steel Buildings, American Institute of Steel Construction (AISC), Chicago, 2022.
- [29] Liu, Z., Xu, W., Zhu, L., Jiang, Y., Wang, Y., Ye, Q., Dai, P., & Chen, B. (2026). Buckling behaviour of hybrid stainless steel girders under concentrated loading. *Engineering Structures*, 346, 121635.
- [30] ABAQUS version 2022 [Computer software]. Dassault Systems, Waltham, MA, 2022.
- [31] ISO 6892-1: 2009. Metallic Materials-Tensile Testing-Part 1: Method of Test at Room Temperature. International Organization for Standardization, Geneva, Switzerland, 2009.
- [32] Fang, Z., Roy, K., Padiyara, S., Chen, B., Raftery, G. M., & Lim, J. B. (2023). Web crippling design of cold-formed stainless steel channels under interior-two-flange loading condition using deep belief network. *Structures*, 47, 1967-1990.
- [33] Feng, R., Tang, C., Chen, Z., Roy, K., Chen, B., & Lim, J. B. (2021). A numerical study and proposed design rules for stress concentration factors of stainless steel hybrid tubular K-joints. *Engineering Structures*, 233, 111916.
- [34] Dai, Y., Roy, K., Fang, Z., Chen, B., Raftery, G. M., & Lim, J. B. (2024). Buckling resistance of axially loaded cold-formed steel built-up stiffened box sections through experimental testing and finite element analysis. *Engineering Structures*, 302, 117379.
- [35] Wang, Y., Chen, B., Wang, W., Ye, Q., Liu, J. Z., Li, B., & Wang, Z. (2025). Experimental and numerical study of stainless steel beams with different opening shapes in the marine environment. *Ocean Engineering*, 342, 123218.
- [36] Ye, Q., Nie, H., Wang, Y., Xi, Z., Bi, S., Fu, Z., Chen, B. (2025). Testing, simulation and design of perforated-web high-strength stainless steel girders in shear. *Journal of Building Engineering*, 145552.
- [37] Wang, Y., Chen, B., Wang, J., Luo, L., Li, B., Ye, Q., & Hai, L. (2025). Effect of web openings on the patch loading resistance of QN 1803 high-strength stainless steel plate girders. *Thin-Walled Structures*, 210, 113065.
- [38] Jiang, Y., Li, L., Zhu, L., Xu, W., Wang, Y., Chen, B., Chi, Y., Wu, G. (2025). Design provision assessment for localized-loading resistance of welded stainless steel I-beams with web openings. *Case Studies in Construction Materials*, 22, e04854.
- [39] Zhu, L., Jiang, Y., Liu, Z., Wang, Y., Wang, W., & Chen, B. (2024). Web crippling behaviour of high-strength aluminium alloy channel-shaped members with strengthened web holes: Numerical study and new design rules. *Structures*, 65, 106690.
- [40] Wang, Y., Luk, W. S., Song, Y., Yam, M. C., Lin, X. M., & Zhang, P. (2025). Net section failure of stainless steel staggered bolted connections. *Thin-Walled Structures*, 217, 113884.
- [41] Wang, Y., Chen, B., Dai, P., Wang, Y., Song, Y., Jiang, K., & Hai, L. (2025). Experimental and numerical study on lateral-torsional buckling of welded QN1803 high-strength stainless steel I-girders. *Thin-Walled Structures*, 212, 113190.
- [42] Gao, L., Wang, Y., Wang, J., Yuan, J., Chen, B., & Bai, L. (2025). Experimental and numerical investigation on global-stability of welded BS700 high-strength steel beams. *Journal of Constructional Steel Research*, 227, 109373.
- [43] Xu, D., Wang, Y., Liu, X., Chen, B., & Bu, Y. (2023). A novel method and modelling technique for determining the initial geometric imperfection of steel members using 3D scanning. *Structures*, 49, 855-874.
- [44] Wang, Y., Chen, B., Dai, P., Chen, Y., Zhang, Z., Lu, P., & Huang, C. (2025). Design recommendations for perforated S32001 high-strength stainless steel girders under concentrated loading. *Structures*, 78, 109295.
- [45] Chen, B., Wang, Y., Wang, Y., Luo, L., Li, B., Lim, J. B., & Dai, Y. (2024). New design recommendations for QN1803 high-strength stainless-steel plate girders with web openings in shear. *Journal of Constructional Steel Research*, 221, 108907.